Coordinated Control of Unmanned Air Vehicles

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1 Executive Summary

This report describes research performed by the author while working as a Visiting Scientist during a ten-week period in the summer of 1999 at the Air Force Research Laboratory, Air Vehicles Directorate. This work was supervised by Phillip Chandler. The focus of the research effort was the coordinated control of unmanned air vehicles (UAVs). The specific problem addressed dealt with coordination of rendezvous of multiple UAVs.

The report is organized as follows: Section 2 gives an introduction to UAVs, their potential advantages and proposed uses. Section 3 discusses the motivations and challenges associated with the coordination of activities of multiple UAVs. Section 4 discusses the coordination of rendezvous with Section 4.1 introducing a general problem and Section 4.2 discussing in detail a simplified version of the rendezvous problem and the method of solution employed in this research. Section 5 provides conclusions and potential future research directions for the specific problem addressed.

2 Introduction

Unmanned air vehicles have the potential to significantly improve the operational effectiveness of the United States Air Force. Indeed, their potential for future use has been demonstrated in a limited fashion in recent confrontations in the Balkans where UAVs were successfully used for reconnaissance. The potential advantages of UAVs over manned aircraft are significant and motivate the development of advanced UAV technologies. These advantages include the following:

Maximum maneuverability. For a UAV, there are no constraints imposed by the pilot's physiological limitations. Where manned aircraft are limited to maneuvers in the 9 g range, unmanned air vehicles may be able to extend their performance envelope to approach performance limits achieved by modern missile systems (40 to 50 g). Negative-g maneuvers also become a possibility.

Low risk to human operators. UAVs are suitable for missions where the risk to pilots would be deemed unacceptably high. For example, Suppression of Enemy Air Defense (SEAD) missions involve attacking well-defended locations where risks to aircraft attacking in the earliest stages of the offensive are extremely high. In this situation, UAVs could be used in initial attacks to degrade or destroy enemy air defense systems, while manned aircraft could be used in subsequent bombing sorties.

Significant weight savings. Because there is no pilot or cockpit in a UAV, there is significant weight savings. Most of the weight savings is not from the pilot, but from the support hardware that a pilot requires (e.g., ejection system, displays, control inputs, etc.). This weight savings can be dedicated to increasing the payload (ordinance or sensing systems) or to improving performance by maintaining a lighter-weight platform.

Lower cost. UAVs will cost less than their manned-aircraft counterparts. Much of the cost savings will come from the reduced need for multiple highly trained pilots per aircraft. Other savings will result from the mass production of a common UAV platform capable of fulfilling multiple roles. For example, the role of a large payload bomber could be accomplished by many smaller payload UAVs operating in a cooperative fashion.

Superior coordination. By taking advantage of modern sensing, computing, and communication capabilities, UAVs have the potential to offer superior coordination of activities among aircraft. Currently coordination among aircraft is accomplished by visual and voice communication among pilots. This limits in a fundamental way the level of coordination that can be attained among aircraft. It is assumed that coordination strategies for UAVs will draw on the superior cognitive and decision-making capabilities of humans, while also taking advantage of both the superior computing, sensing, and communication capabilities that modern technology provides as well as the maximum maneuverability available to UAVs.

New operational paradigms. From a strategic standpoint, current operational methods for military aircraft have been devised with the underlying assumption that a human pilot would be in control of each aircraft. With UAVs, this will not be the case. To take full advantage of UAVs, it will be necessary to develop new operational paradigms that draw on the unique strengths and capabilities of UAVs. In some ways these new paradigms will be fundamentally different from current practice.

Unmanned air vehicles have the potential to fulfill many of the same duties performed today by manned aircraft. Some of the possible missions include [1]:

- Intelligence/Surveillance/Reconnaissance

- Communications Node – Relay, Gateway
- Jamming/Decoys
- Suppression of Enemy Air Defenses (SEAD)
- Theater/Cruise Missile Defense
- Fixed Target Attack
- Moving Target Attack
- Air-to-air Combat.

While each of these types of missions could be benefited by individual UAVs operating autonomously (with respect to other UAVs), it is clear that teams of UAVs *with an effective coordination strategy* will lead to superior performance and an efficient utilization of resources. The possibility of using multiple less expensive, less complex UAVs to accomplish the mission of a single complex (and more costly) system with superior performance and greater robustness provide substantial motivation for research into the issues of coordinated control.

3 Major Issues in Multiple Vehicle Coordination

Much work remains to enable levels of cooperation among UAVs necessary to accomplish missions of interest to the Air Force. Some of the research issues that are critical to enabling the development of cooperative UAV systems are discussed below.

3.1 Challenges of Coordination

Coordination implies the existence of multiple vehicles, each having assets and capabilities of value, and of a team goal or mission objective that is desired to be accomplished. What is needed is a means by which coordination can take place among the vehicles composing the team. Coordination of multiple vehicles is challenging for a number of reasons. In addressing coordination problems, many issues and questions have yet to be addressed in a way that is generally applicable to a variety of problems.

Coordination implies complexity. A team of UAVs is a system composed of many systems. A fundamental question is how should these large-scale, complex problems be decomposed so that they are not only tractable, but so that complexity of the analysis scales linearly with the number of vehicles. What are the guiding principles that should drive the decomposition of these complex problems?

Coordination requires communication. To coordinate an activity, some information must be shared among the members of the team. Key questions include: How should information be exchanged among vehicles to maximize the coordination? What information should be shared? How frequently should information be exchanged? To which vehicles should information be passed? It is clear that full information about each vehicle cannot be shared with all other vehicles on the team due to the cost involved. Communication among UAVs will be limited by available bandwidth and by stealth considerations. It is also clear that the level of coordination attainable by a team of UAVs will be dependent on the quality and rate at which information is communicated among vehicles.

Coordination implies coupling. What one vehicle does affects the behavior of other vehicles (to varying degrees depending on the team objective). An important issue to address is how can UAVs be controlled so that any negative effects of this coupling are minimized.

Coordination requires arbitration. For coordination to be carried out in a way conducive to achieving team objectives, some mechanism for joint decision making or arbitration must be in place. In determining its actions, it is important that each vehicle be aware of what is best in terms of achieving the team objective. A major issue to be addressed is how to maximize the effectiveness of the UAV team. An action that is best for an individual UAV may not be best for the UAV team. Clearly, team and individual objectives are often in conflict. Some arbitration strategy must be developed to resolve such conflicts.

Coordination takes time. The planning, computation, and communication performed by UAVs in a coordination task take time. The effects of latency, delay, and asynchronous information on the quality of coordination must be examined. Strategies for overcoming these ever-present negative effects must be developed.

In general terms, research is needed in several areas to enable straightforward solutions to broad classes of problems. First, general approaches for defining coordination structures or architectures are needed. Second, a mathematical framework for analyzing and synthesizing multiple-vehicle coordinated-control systems must be developed. Finally, general strategies for addressing the issue of complexity are needed.

3.2 Potential Coordinated Control Applications

As examples of situations where multiple cooperating UAVs would be advantageous, consider the following scenarios:

Coordinated Sensing Using *passive* radar that provide only azimuth information about a target to individual UAVs, a team of three or more UAVs could be used to triangulate the position of a target by coordinating the sensing task among the UAVs. Not only does this provide the capability of determining the position of a target by using a passive sensor, this sensing strategy could be used to direct guided munitions toward a target. As depicted in Figure 1, this would eliminate the need for an expensive seeker which would be lost as the missile strikes the target. Some research issues in achieving such a task include uncertainty in UAV positions, sensing from moving platforms, timing of the sensing by individual UAVs, and coordination of the task among UAVs.

Coordinated Jamming A single UAV can only jam a sector of the coverage of an enemy radar. Multiple UAVs could jam the full coverage of an enemy radar by coordinating their flight paths and jamming signals. Issues include determination of efficient jamming strategies for multiple vehicles and cooperative jamming under changing conditions due to a UAV loss or new threats.

Timed Attack In a SEAD-type mission, the timing of the attack is critical to maintain the element of surprise, thereby maximizing the survivability of the UAVs as well as their lethality. The timing of the attack may require certain vehicles to be in certain places at certain times. For example, it may require that decoys arrive at a specified time to distract enemy sensing systems, followed by the synchronous arrival of multiple bombers at the target location. Such synchronization is made difficult by uncertainties in target and threat locations: a pop-up threat would require significant coordination

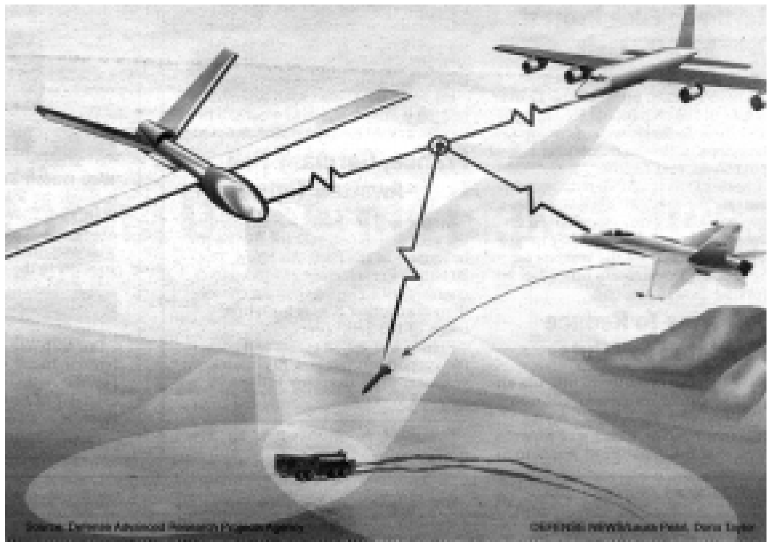

Figure 1: Coordinated Sensing Mission

of replanning efforts among aircraft to ensure simultaneous arrival at the target.

Seek and Destroy In this type of mission, the objective is to search out and destroy a mobile enemy target. Initially a group of vehicles would be widely distributed in a search mode where the battle area would be canvassed efficiently in a coordinated way. Upon detection of a target, a subgroup of vehicles would locate the target by triangulation. Finally, an attack would be coordinated where multiple vehicles would launch munitions toward the target. Successful completion of such a mission requires a high degree of coordination among UAVs.

To enable the effective use of UAVs in the situations outlined above, strategies for the design and analysis of cooperative multiple-vehicle systems must be developed and validated.

4 Coordination of Rendezvous

In this research, the subject of coordinated control of UAVs is addressed in the context of a specific problem: the rendezvous of multiple vehicles at a predetermined target location. The particular problem addressed has the advantages of being tractable in the near term (in its simpler forms), of being realistic and of value, and of providing insights into coordination in general. This section first gives a general description of the rendezvous problem, followed by a detailed description of a specific rendezvous problem with a simplified trajectory planning component.

4.1 General Problem Description

This section outlines a general rendezvous problem and some of the specific coordination issues involved in it solution. A schematic representation of the rendezvous problem considered is shown in Figure 2. The objective was for two (or more) UAVs to arrive at specified points on the boundary of the detection region surrounding a SAM site simultaneously. The rationale for this objective was to maximize the survivability and lethality of the UAVs. It was required that the UAVs avoid threats and manage their fuel to enable a safe return to base. These are typically competing constraints for the UAVs in that avoiding threats involves longer paths and high speeds (to minimize time in hostile airspace), while fuel conservation requires slow speeds and short paths to the target. In this effort, the coordination of rendezvous was subject to changes in the environment such as unknown pop-up threats and uncertainty in the target location.

From a synthesis perspective, the objective was to come up with a strategy that yields the best solution (or nearly so) to the problem at hand — in this case, the coordination of rendezvous. In particular, the problem became one of determining the best time to rendezvous taking into account each vehicle's exposure to threats and fuel availability.

In Figure 2 the two UAVs are enroute to the target along nominal preplanned trajectories indicated by dotted lines. When an unknown threat is detected by UAV #2, it becomes necessary to determine a new estimated time until arrival (ETA) for the team and to plan new trajectories accordingly. The figure depicts new trajectories that will enable the rendezvous to occur. Clearly, the new trajectory for UAV #1 is suboptimal when its fuel and threat costs alone are considered. However, when the costs to the team as a whole are considered, a longer team ETA, which allows simultaneous arrival of both UAVs and safe passage of UAV #2, is considered better.

A central component of the rendezvous problem is the trajectory planning involved for each of the vehicles. Even for the constant altitude 2-D problem posed here, the trajectory planning issues are complex and challenging and require a significant research effort on their own [2]. To enable

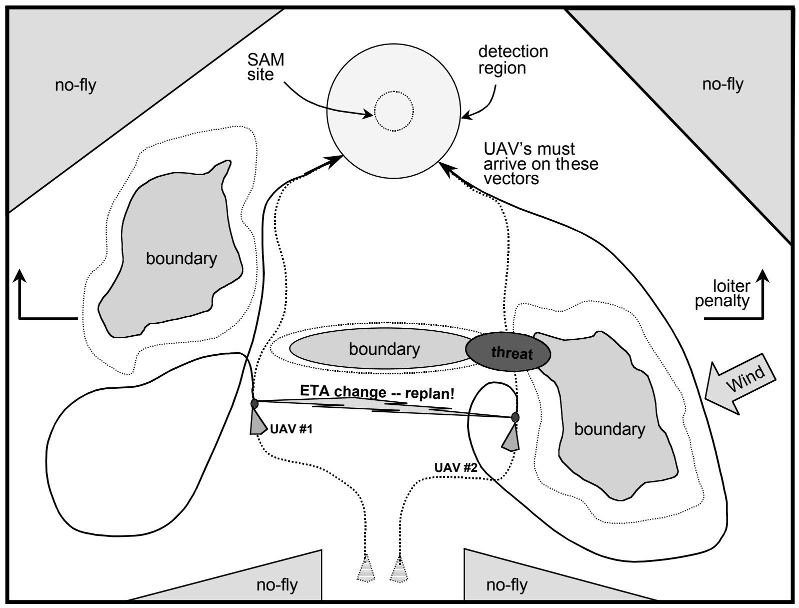

Figure 2: Coordination of Rendezvous

focus on research issues involved in coordination, a rendezvous problem with a less complex trajectory planning component was devised.

4.2 Detailed Problem Solution

The flight trajectory planning issues associated with the rendezvous problem described in Section 4.1 are sufficiently complex to pose a significant technical challenge. Because of the limited time available, the decision was made to formulate a rendezvous problem that incorporated many of the same coordination issues as the problem described above, but that had a significantly simpler planning component. This problem is described in detail below.

Figure 3 shows a schematic representation of the simplified rendezvous problem. Features of the current problem include: two or more UAVs (in this case three), a single target in a known location, battle area divided into low threat and high threat regions by a threat boundary, and threats that "pop up" along the threat boundary. The objective, as before, is to have the three UAVs arrive at the target simultaneously in a way that maximizes the survivability of the entire team of UAVs.

Each of the vehicles was modeled as having first-order velocity dynamics

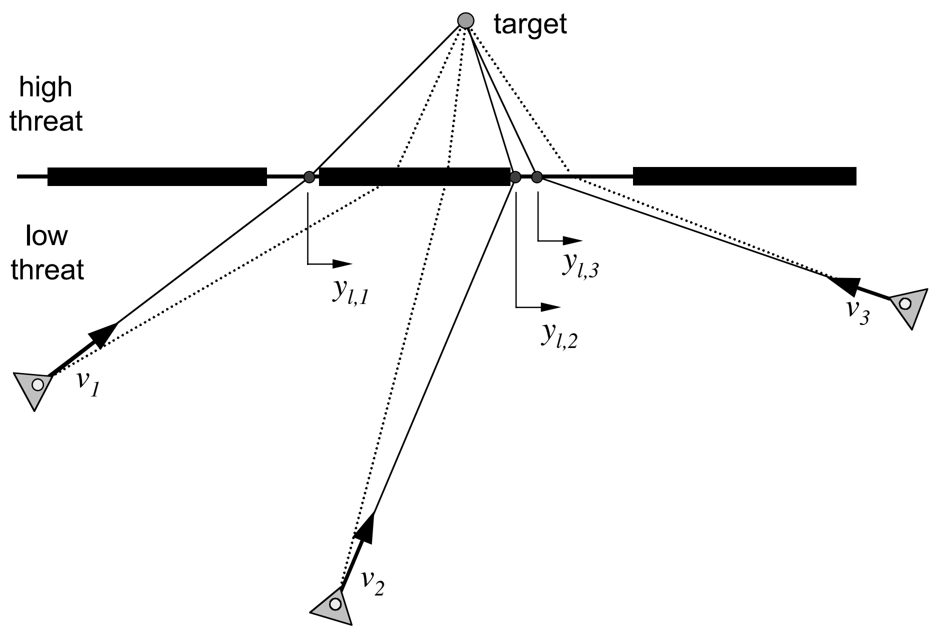

Figure 3: Simplified Rendezvous Problem

and first-order heading dynamics. The vehicle velocities were limited to the range of 270 to 330 mph. The vehicle heading rates were limited to $\pm$ 10 deg/sec.

The UAV team mission for this problem is carried out in phases as Figure 4 depicts. In phase I, the UAVs are enroute to the forward edge of the battle area. Upon arriving at the forward edge, phase II commences wherein optimal trajectories are planned for the team assuming no threats along the boundary. The UAVs travel along these trajectories until threats along the boundary are detected. This signifies the commencement of phase III. Trajectories are then planned taking into account the locations of threats on the threat boundary. The vehicles travel along these trajectories until reaching the boundary, where phase IV begins. In phase IV, the UAVs vector to the target, arriving simultaneously.

Trajectories during the mission are calculated to maximize the survivability of the team, while ensuring that the rendezvous at the target occurs as desired. The survivability of the vehicles is quantified by two cost func-

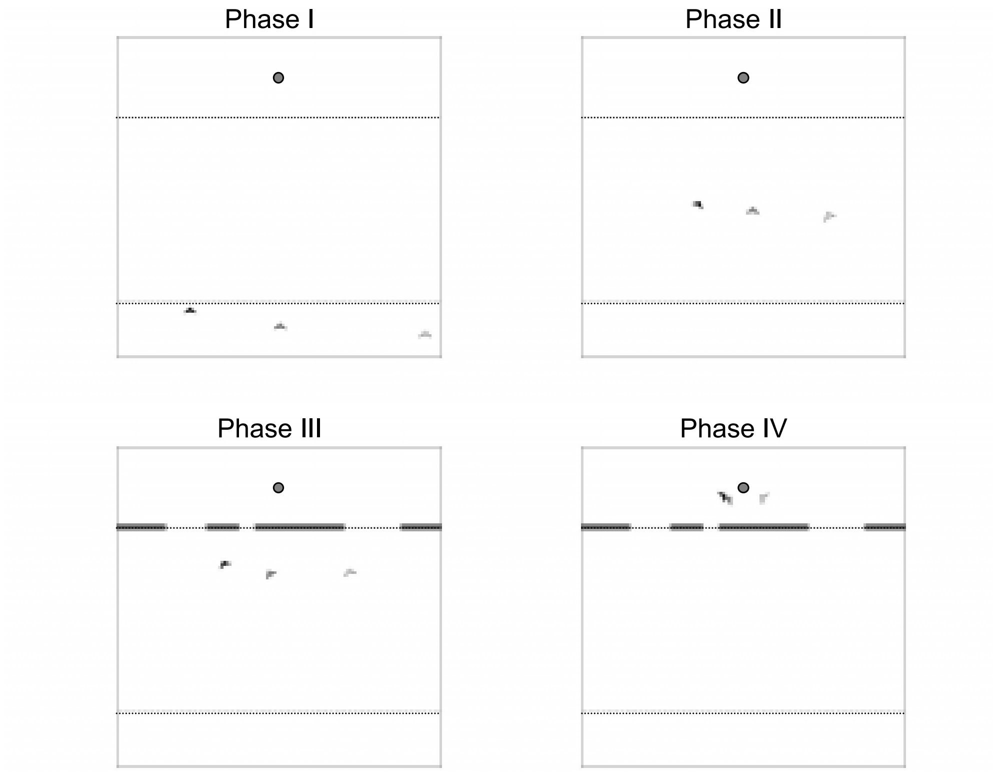

Figure 4: Four Phases of the Rendezvous Mission

tions representing the fuel cost J_f and the threat cost J_t to each vehicle:

$$J_f = C_f v(l_l + l_h) \tag{1}$$

$$J_t = C_l \left(\frac{l_l}{v}\right) + C_h \left(\frac{l_h}{v}\right), \tag{2}$$

where v is the velocity of the UAV, l_l is the path length in the low-threat region, and l_h is the path length in the high-threat region. The constants C_f, C_l, and C_h are weighting factors chosen by the mission designer and effect the determination of what is "best" for each vehicle and the team.

Figure 5 depicts the geometry associated with the problem. The benefit of considering this problem is that the trajectory planning problem for each UAV has been reduced from a complex two-point boundary value or grid search problem to the selection of two parameters that define the trajectory: y_l and v. This is done while preserving the primary coordination aspects of the rendezvous problem, thereby allowing research efforts to focus on coordinated control issues rather than trajectory planning issues.

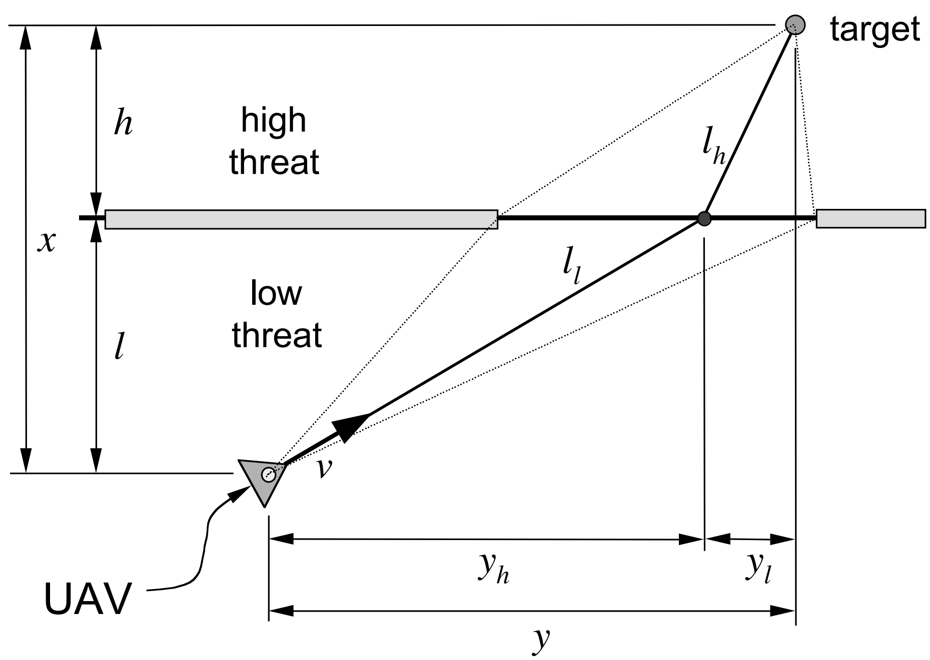

Figure 5: Rendezvous Geometry

Transitions between the phases of the mission shown in Figure 4 are event driven. For example, the transition from phase I to phase II occurs when the forward edge of the battle area is reached. These transitions are handled by the Rendezvous Manager finite-state machine, which resides on each of the UAVs. Figure 6 shows a statechart [3] representation of the Rendezvous Manager. The Rendezvous Manager shown here is very simple and lacks some of the capabilities that a more detailed state machine might have. The focus of the research effort presented here was not on the development of a fully-functional manager capable of handling the full array of possible events that might occur, but rather on the issue of finding a good way to coordinate the activities of multiple UAVs. Here the focus was on the algorithms carried out during the transitions. For each vehicle, the Rendezvous Manager produces the necessary desired velocity v and heading commands (calculated from y_l) to coordinate the rendezvous.

With the rendezvous task defined, the task of finding the best way to coordinate rendezvous can be posed as an optimization problem. The problem becomes one of choosing $y_{l,i}$ and v_i, $i = 1, 2, 3$, that result in an arrival time t_a that minimizes the cost

$$\sum_{i=1}^{3} (J_{f,i} + J_{t,i})$$

while constraining the UAVs to arrive at the target simultaneously. In the given mission scenario, this optimization must be carried out at the commencement of phases II and III. This optimization could be carried out in a centralized manner by having all state, threat, and fuel information for each UAV communicated to a central location where a large-scale optimization problem would be solved and finally trajectory information communicated back to individual UAVs. This approach is undesirable for a number of reasons. First, it involve communication of massive amounts of information, which is undesirable for stealth and implementation reasons. Second, it involves the solution of a very large and complex optimization. This will not be possible at the near-realtime rates required. Furthermore this approach does not scale well with the number of vehicles and requires a powerful computer at a central location. Third, this approach is not robust in that it is sensitive to failures of the main computer system. If this system fails, mission effectiveness is jeopardized.

A preferred approach is to decentralize the computational solution of the optimization problem by allowing each UAV to compute its own trajectory that is optimal with respect to the needs of the team. The challenge here is determine what information must be communicated among team members to give them an awareness of the situation of the other team members so that each may calculate solutions that are optimal from a team perspective. As part of this research, a decomposition strategy was formulated that allows these optimizations to be carried out in a manner that is decentralized from a computational perspective, but that is centralized in the sense that trajectories are planned taking into consideration the situation of all of the UAV team members.

Although the solution strategy developed for this problem is general enough to encompass a wide variety of coordination problems, it is most easily explained in the context of the specific rendezvous problem to which it was first applied. The method developed has similarities to decomposition strategies developed for multidisciplinary optimization purposes [4, 5]. For

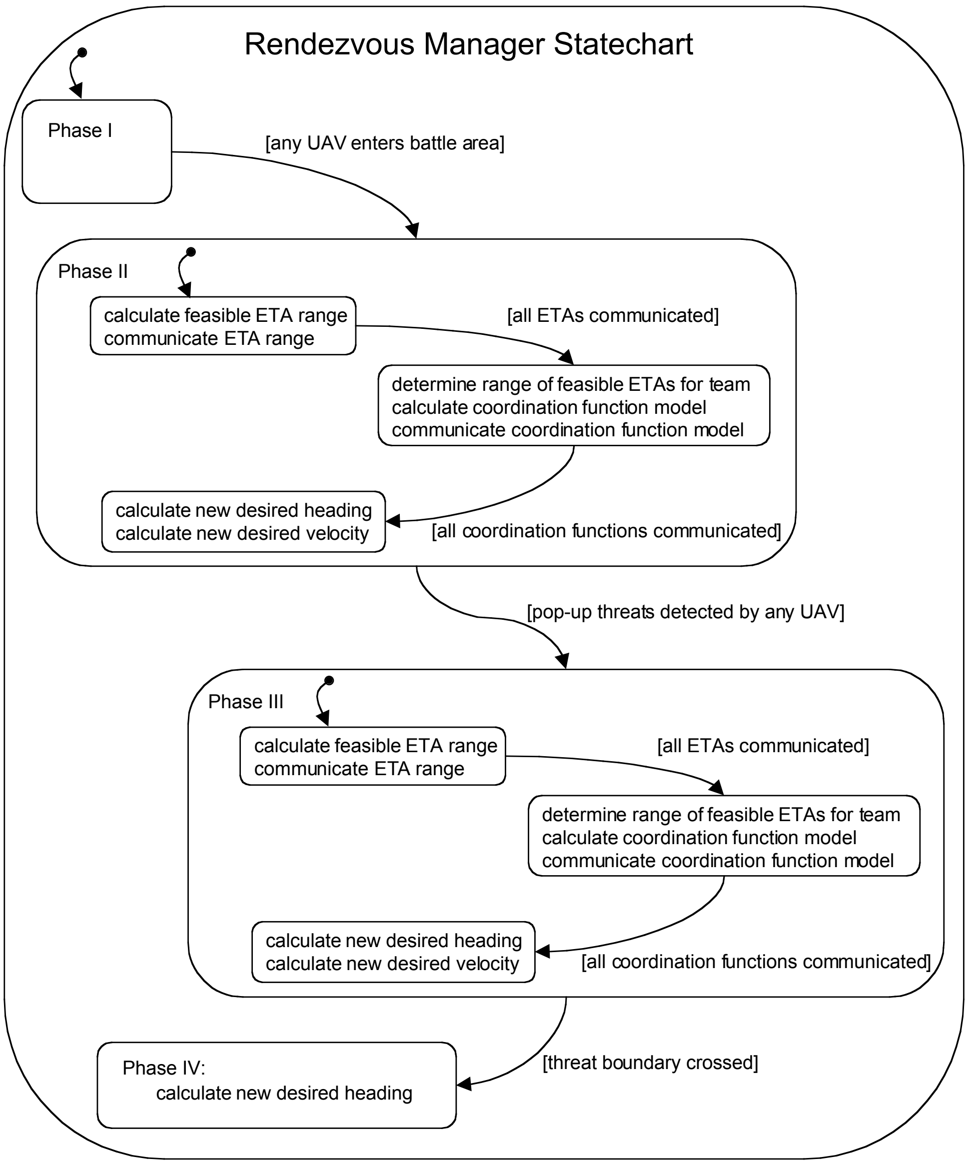

Figure 6: Rendezvous Manager Statechart

the coordination problem, the purpose of decomposition is to break up a single, very large optimization problem into smaller, more tractable optimization problems that will allow computations to be decentralized among the UAVs, that will require only modest communication among UAVs, while taking into account the threat and fuel situation of each UAV.

The diagram of Figure 7 shows the decomposition strategy pursued. At the team level, the task is to choose an estimated time until arrival (ETA or t_a for brevity) for the team that maximizes the probability of a successful mission, which means that threats are avoided and fuel conserved by individual vehicles, while ensuring that the UAVs arrive at the detection region simultaneously. At the vehicle level, the task for each UAV is to plan a trajectory that will allow the team ETA to be matched, that maximizes its own survivability. This must be done subject to constraints on the dynamics of the UAV. The team ETA is called a *coordination variable* because by constraining it to be the same for all of the UAVs, the coordination of rendezvous among the UAVs is achieved.

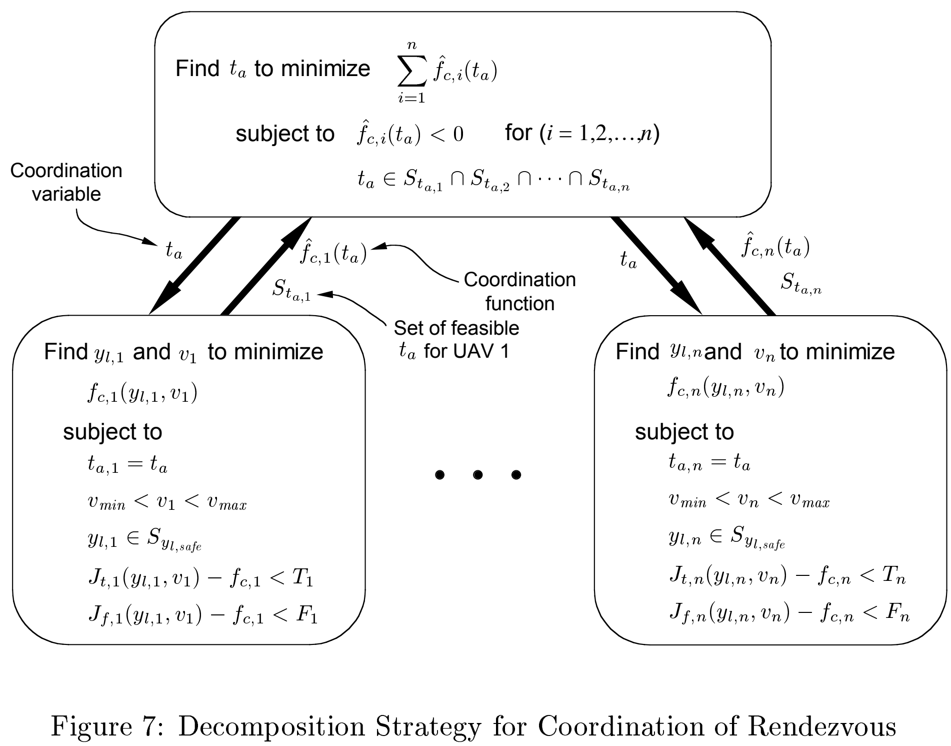

Figure 7: Decomposition Strategy for Coordination of Rendezvous

The trajectory planning elements of the mission are event driven and occur upon entry into the battle area (beginning of phase II) and upon the detection of a threat (beginning of phase III). Upon initiating phase II or phase III, each UAV calculates a function describing its own costs (threat and fuel) versus ETA. This function is termed a *coordination function* since it describes how changes in the team ETA (coordination variable) affect the survivability of an individual UAV. An estimate of the coordination function is calculated by determining the costs for various ETA values and then passing this information to the team level where they are used to calculate an optimal ETA for the team. This optimal team ETA is then passed back to the vehicle level where it is used to determine new trajectories for each of the vehicles.

A key issue here is the calculation of the coordination function. In this problem the ETA, the fuel cost, and the threat cost for each UAV are functions of the trajectory parameters y_l and v. For a given ETA, the value of the coordination function f_c is determined by finding values for y_l and v that maximize the feasibility of the constraints on fuel cost and threat cost. As the costs constraints given by

$$J_{f,i}(y_{l,i}) - f_{c,i} < F_i$$
$$J_{t,i}(y_{l,i}) - f_{c,i} < T_i$$

indicate, the feasibility with respect to threat and fuel cost constraints is maximized as $f_{c,i}$ is made more negative. Since many combinations of $y_{l,i}$ and v_i can produce the same ETA, the objective becomes to find those values that give the minimal value for $f_{c,i}$. This is done for multiple ETA values over the range of achievable ETAs to form a functional relationship between feasibility and ETA. This functional relationship can be encoded simply by vectors of feasibility and ETA data or by performing polynomial curve fits through the data. For simplicity, vectors of coordination function data are used here. Determination of the coordination function is depicted graphically in Figure 8.

For simplicity of presentation, it is assumed that the constraint limits, T_i and F_i, are equal. In Figure 8, the dashed lines represent values of J_t for changing v and constant y_l, while the dash-dotted lines represent values of J_f for changing v and constant y_l. The intersections of the dashed and dash-dotted lines represent points where the feasibility of the cost constraints is maximized for particular ETA values. These points are used to form the estimate of the coordination function $\hat{f}_{c,i}(t_a)$.

With the coordination functions determined for each UAV, the system level optimization to determine the best ETA can be performed. The optimization objective is simply to choose the ETA that minimizes the sum

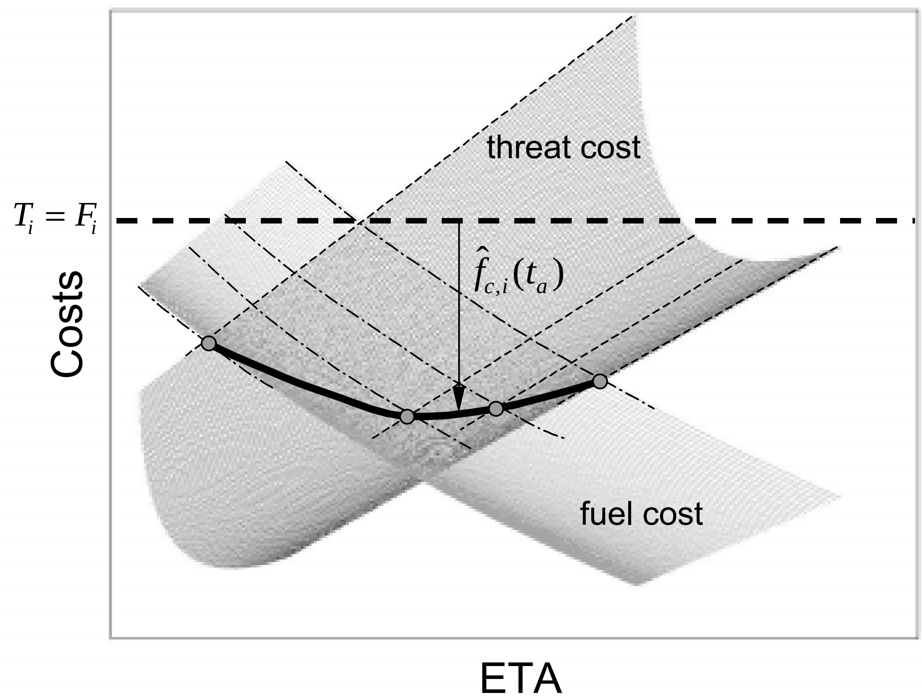

Figure 8: Coordination Function Determination

of the coordination functions from each UAV. By doing so, an ETA that is mutually beneficial for all of the UAVs is chosen. Note that at the system level, the coordination function estimates are constrained to be less than zero. This ensures that the chosen ETA will satisfy the threat and fuel constraints at the vehicle level.

Once an optimal ETA is determined, it is passed to the vehicle level where values of y_l and v corresponding to the chosen ETA are calculated. These parameters define the trajectory for each UAV and ensure the simultaneous arrival of the UAVs at the target.

While the decomposition strategy seems to imply a hierarchy with the system-level optimization occurring at a some centralized location. This is not necessarily the case. The optimization at the system level can be carried out on each UAV in a fully decentralized fashion. The strength of the decomposition approach presented here is that the coordination computations can be carried out in a decentralized manner based upon coordination function estimates that capture, in an efficient manner, the essential information required to find a solution that is optimal from a team perspective. Clearly, a critical issue is the estimation and efficient communication of coordination function information among team members.

The rendezvous problem described was simulated under a variety of conditions using the Matlab/Simulink/Stateflow software package. The Stateflow environment provided a straightforward way of developing and implementing the Rendezvous Manager shown in Figure 6. Simulink was used to simulate the dynamics of the UAVs and to interface with the Rendezvous Manager statechart. The software developed to simulate the system has been fully documented and provided to the sponsors of this research.

The results obtained using the decomposition approach closely approximate those obtained by solution of the full-scale optimization problem for the team. The accuracy of the approximation is determined primarily by the accuracy of the coordination function estimates. While developed to deal specifically with rendezvous, the method should be suitable to a variety of coordination problems.

5 Conclusions and Recommendations

The coordinated control of unmanned air vehicles poses significant challenges. The research presented here has addressed the coordination of rendezvous of multiple UAVs at a predetermined target location. As an approach to finding a solution that is best for the team as a whole, a decomposition strategy was developed that allows team-optimal solutions to be computed in a decentralized manner.

Because of the short time frame under which this research was conducted, many important issues remain to be explored and important elements of the solution strategy need further development. Even so, the research effort has been successful to this point and it is hoped that future efforts will continue to provide valuable insights into the problem of multiple vehicle coordination.

In the near term, a number of research issues relating to the specific rendezvous problem addressed should be explored. Tasks and issues to consider include:

- Uncertainty in the target position that is reduced as the UAVs approach the target.

- Multiple targets – one for each UAV.

- Constraining UAVs to arrive at the target on a given vector.
- Triangulation of the target position using three or more UAVs.
- Computation latency associated with trajectory planning and coordination function estimation.
- Efficiency and accuracy of coordination function estimation.
- Increased rendezvous problem complexity by incorporation of a more realistic planning component.
- Application of the decomposition strategy to other coordination problems.

By examining these issues and exploring relevant research in a broad variety of fields, it is anticipated that strategies will be developed enabling progress towards the goal of achieving the coordinated control of unmanned air vehicles.

6 Acknowledgments

The guidance of Phillip Chandler both in defining the rendezvous problem and in working toward a solution has been critical to the success of this effort. In addition, this work has benefitted from the insightful comments of Meir Pachter, Scott Bortoff, and Steve Rasmussen. The support of Siva Banda in providing a summer research opportunity at the AFRL is greatly appreciated.

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